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Experiments in real-time quantum feedback[1]

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Recent advances in quantum optics and atomic physics have enabled experimenters to begin exploring *real-time feedback* in quantum settings [1, 2, 3, 4]. In addition to the practical significance of such work for fields like nanotechnology and quantum information processing, research on quantum feedback probes the fundamental physics of conditional evolution for observed systems. Feedback in quantum settings is generally complicated by the intricacies of 'wave-function collapse' and measurement back-action, so that the proper design of quantum feedback controllers will require accurate quantitative models for the measurement process. The structures of such 'quantum trajectory' theories [5] looks a lot like a quantum version of Kalman filtering, where the conditional evolution of state vectors or density operators is given by successive application of positive maps selected by the measurement results. Preliminary efforts to integrate quantum trajectory theory with the framework of systems and control [6, 7, 8, 9] have proven quite successful in both fundamental studies [10, 11] and in application development [12, 13, 15, 16]. Ongoing work in the theoretical research community now aims at an integration of the quantum feedback formalism with that of open-loop coherent control [17], while experimentalists are focusing on implementing convincing demonstrations of quantum feedback.

Real-time quantum feedback is of interest both for closed-loop control and for adaptive measurement. Similar enabling technologies are required in both classes of application: quantum feedback requires broadband quantum-noise limited measurement and fast digital signal processing (state-space methods will be essential for quantum systems). With a view towards establishing a long-term experimental program in quantum feedback, we have been developing the requisite measurement and processing capabilities in a quantum optical setting [18]. Our first application of these laboratory resources has been to adaptive quantum measurement of optical phase [4, 12], and we have recently begun to extend our activities towards feedback control of atomic degrees-of-freedom such as internal spin state [16] and center-of-mass motion [19].

Adaptive homodyne measurement provides a unique method for uncertainty-limited determination of the phase of very weak pulses of light. Here the quantum aspect of the problem corresponds to the intrinsic uncertainty in the optical phase of (coherent) light pulses generated even by an ideal laser, which can roughly be associated with natural vacuum fluctuations of the electromagnetic field. We say that a procedure for measuring some physical quantity is 'uncertainty limited' if its inherent inaccuracy is sufficiently small to reveal the intrinsic quantum uncertainty in that observable. Standard optical techniques for measuring the phase of laser pulses suffer from systematic inaccuracy that prevents them from reaching the uncertainty limit. Balanced heterodyne detection has been widely regarded as the best practicable phase-measurement procedure, and its ideal performance can be shown to be a factor of two worse than the uncertainty limit for optical coherent states.

Using theoretical techniques from quantum optics, Wiseman predicted that the use of an optimized phase-lock loop would make it possible to beat the performance of heterodyne detection, and to approach the quantum uncertainty limit for pulses of mean photon number of order ten or higher [12]. Our recent experimental results validate Wiseman's analysis, showing that adaptive homodyne estimation of the optical phase of weak coherent laser pulses achieves measurement variances closer to the fundamental quantum uncertainty limit than any previous technique. Our results probe the ultimate quantum limit of optical phase-lock loops, with clear evidence of lock acquisition on the basis of merely one or two photons of signal.

The next stage of our experimental research will involve coupling a weak optical probe to atomic variables, then using our quantum-noise limited optical measurement techniques to infer evolution of the atomic state. Both the atomic spin and atomic motion can be coupled to light such that the atom(s) imparts a phase-shift to the optical probe beam whose magnitude depends on the dynamical variable in question. Actuation can then be achieved using magnetic fields or Raman laser pulses in the spin case, or mechanical forces induced by magnetic or optical fields in the motion case. Quantitative testing of the predicted performance of various control algorithms will be pursued as a test of both quantum trajectory theory and robust synthesis methods for quantum feedback control.

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